THE FINAL FATE OF BINARY NEUTRON STARS: WHAT HAPPENS AFTER THE MERGER?

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The merger of two neutron stars usually produces a remnant with a mass significantly above the single (nonrotating) neutron star maximum mass. In some cases, the remnant will be stabilized against collapse by rapid, differential rotation. MHD-driven angular momentum transport eventually leads to the collapse of the remnant's core, resulting in a black hole surrounded by a massive accretion torus. Here we present simulations of this process. The plausibility of generating short duration gamma ray bursts through this scenario is discussed.

1. Introduction

The merger of binary neutron stars is now one of the favored hypotheses for explaining short gamma ray bursts (GRBs). According to this scenario, after the merger, a stellar-mass black hole (BH) is formed with an ambient accretion torus with ~ 1–10% of the total mass. Energy extracted from this system by MHD processes or neutrino radiation powers the GRB fireball. The viability of this model depends on the presence of a significantly massive accretion disk after the collapse of the remnant following merger, and the presence of a baryon-poor region above the accretion disk.

A typical binary neutron star system has total mass 2.6–2.8$M_\odot$,[1] much larger than the spherical neutron star maximum mass $M_{\rm TOV}$. However, the remnant is also rapidly and differentially rotating. Mass limits for nonrotating stars and for rigidly rotating stars (the *supramassive* limit, $M_{\rm sup} \approx 1.2 M_{\rm TOV}$) can be significantly exceeded when differential rotation is present.[2] Stars with masses greater than $M_{\rm sup}$ are called *hypermassive* stars. Thus, the remnant may form a hypermassive neutron star (HMNS). General relativistic hydrodynamic simulations have shown that just after the merger, either a black hole or a HMNS is formed.[3] A BH forms promptly if the total mass of the system, M, is larger than a threshold mass $M_{\rm thr} \approx 2.8 M_{\odot}$. In this case, far less than 1% of the matter remains outside the horizon, which is unfavorable for GRBs. On the other hand, for $M < M_{\rm thr}$, a HMNS forms.

These HMNSs may survive for many orbital periods. However, on longer timescales magnetic fields will transport angular momentum and may trigger gravitational collapse. Two important mechanisms which transport angular momentum are magnetic braking[2,4] and the magnetorotational instability (MRI).[5] Magnetic breaking transports angular momentum on the Alfvén time scale,[2,4] $\tau_A \sim R/v_A \sim 10^2 (B/10^{12}\ {\rm G})^{-1}$ s, where R is the radius of the HMNS. MRI occurs wherever angular velocity Ω decreases with cylindrical radius ϖ. This instability grows exponentially with an e-folding time of $\tau_{\rm MRI} = 4\,(\partial\Omega/\partial \ln \varpi)^{-1}$,[5] independent of the field strength. For the HMNS model considered here, $\tau_{\rm MRI} \sim 1$ ms. The length scale of the fastest growing unstable MRI modes, $\lambda_{\rm MRI}$, does depend on the field strength: $\lambda_{\rm MRI} \sim 3$ cm $(\Omega/4000 s^{-1})^{-1}$ $(B/10^{12}{\rm G}) \ll R$. When the MRI saturates, turbulence consisting of small-scale eddies often develops, leading to angular momentum transport on a timescale much longer than $\tau_{\rm MRI}$.[5]

2. Simulations

To determine the final fate of the HMNS, it is necessary to carry out magnetohydrodynamic simulations in full general relativity. Such simulations have only recently become possible. Duez *et al.*[6] and Shibata and Sekiguchi[7] have developed new codes to evolve the full Einstein-Maxwell-MHD system of equations self-consistently. These codes have since been used to simulate the evolution of magnetized hypermassive neutron stars,[8,9] and implications for short GRBs have been investigated.[10]

We assume axisymmetry and equatorial symmetry in all our simulations. We use uniform computational grids with sizes up to 500×500. To model the remnant formed in binary merger simulations, we use as our initial data an equilibrium HMNS, a $\Gamma = 2$ polytrope, with mass $M = 1.7 M_{\rm TOV} = 1.5 M_{\rm sup}$ and a rotation profile chosen so that the ratio of equatorial to central Ω is $\sim 1/3$. (We find that an HMNS with a more realistic equation of state evolves similarly.[9,10]) We add a poloidal magnetic field with strength proportional to the gas pressure. The initial magnetic pressure is set much smaller than the gas pressure, but not so small that $\lambda_{\rm MRI}$ cannot be resolved. Therefore, we set $\lambda_{\rm MRI} \approx R/10$, corresponding to $B \approx 10^{16}$ G and $\max(B^2/P) \sim 10^{-3}$.

In our evolutions, the effects of magnetic winding are observed in the generation of a toroidal B field which grows linearly with time during the early phase of the evolution, and saturates on the Alfvén timescale. The effects of MRI are observed in an exponential growth of the poloidal field on the $\lambda_{\rm MRI}$ scale, a growth which saturates after a few rotation periods. The magnetic fields cause angular momentum to be transported outward, so that the core of the star contracts while the outer layers expand. After about 66 rotation periods, the core collapses to a black hole.

Using singularity excision,[11] we continue the evolution to a quasi-stationary state. The final state consists of a black hole of irreducible mass $0.9M$ surrounded by a hot accreting torus with rest mass $0.1M$ and a collimated magnetic field near the polar region. At its final accretion rate, the torus should survive $\sim$10ms. The torus is optically thick to neutrinos, and we estimate that it will emit $\sim 10^{50}$ergs in neutrinos before being accreted. We also find that the region above the black hole is very baryon-poor. All these properties make this system a promising central engine for a short-hard GRB.

In order to study the evolution of the magnetic field more realistically, it will be necessary to redo the evolutions in three dimensions. Also, realistic merger remnants are usually expected to have much smaller magnetic fields than the ones studied here. In an earlier analysis, we modeled the effects of small-scale MRI turbulence as a shear viscosity[12] and found that, if this model is valid, the evolution of the HMNS is qualitatively similar to that shown here.

3. Acknowledgments

Numerical computations were performed at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign (UIUC), and on the FACOM xVPP5000 machine at the data analysis center of NAOJ and the NEC SX6 machine in ISAS, JAXA. This work was in part supported by NSF Grants PHY-0205155 and PHY-0345151, NASA Grants NNG04GK54G and NNG046N90H at UIUC, and Japanese Monbukagakusho Grants (Nos. 17030004 and 17540232).

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